First Stage of Stratospheric Ozone Recovery

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Eun-Su Yang/Georgia Tech
Derek Cunnold/Georgia Tech
Greg Reinsel/U Wisconsin, Deceased
Ross Salawitch/JPL
Joe Zawodny/LaRC
Jim Russell/Hampton U
Pat McCormick/Hampton U
P K Bhartia/GSFC

Presented at
SOSST Meeting
Boulder, CO
15 June 2004

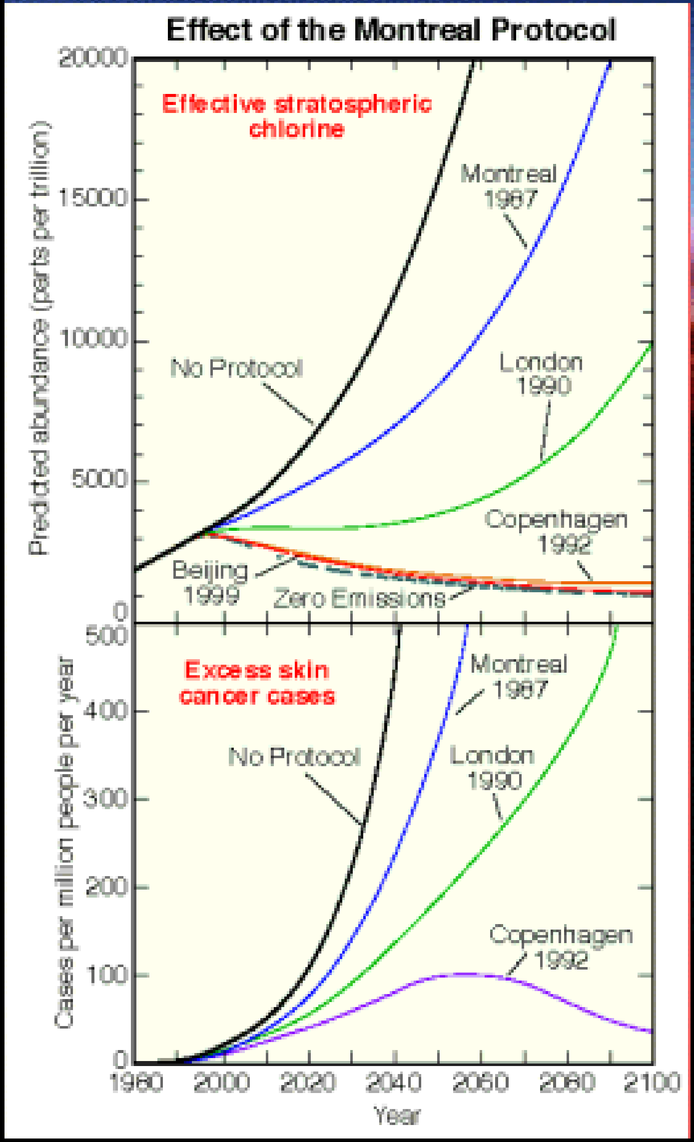
Dedicated to Greg Reinsel
1948 - 2004

Soft spoken gentleman.
Conservative, rigorous scientist.
Consummate statistician.

Brought his considerable statistical expertise to the ozone community for 3 decades, primarily in analysis of Dobson and Umkehr ozone trends.

Originated the idea of applying CUSUM technique to ozone measurements for early detection of changes in secular trends: The critical idea for the success of the work presented today.

Montreal Protocol and Amendments



The 1987 Protocol would not have saved the ozone layer. Neither would have the 1990 London Amendment.
Not until the 1992 Copenhagen Amendment did we have a CFC control strategy that would work (after 50 years of increasing skin cancer cases)

Fahey et al., 20 questions, 2003
http://www.unep.org/ozone/faq.shtml

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Modeling observed ozone trends: In the upper stratosphere, it's the chlorine

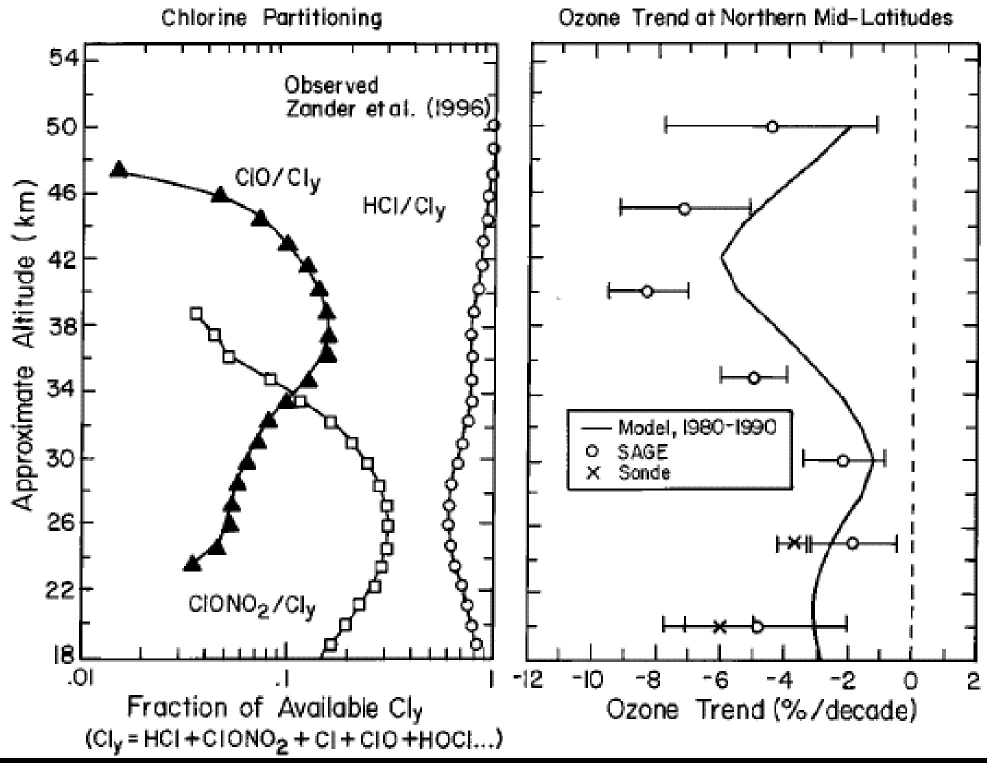
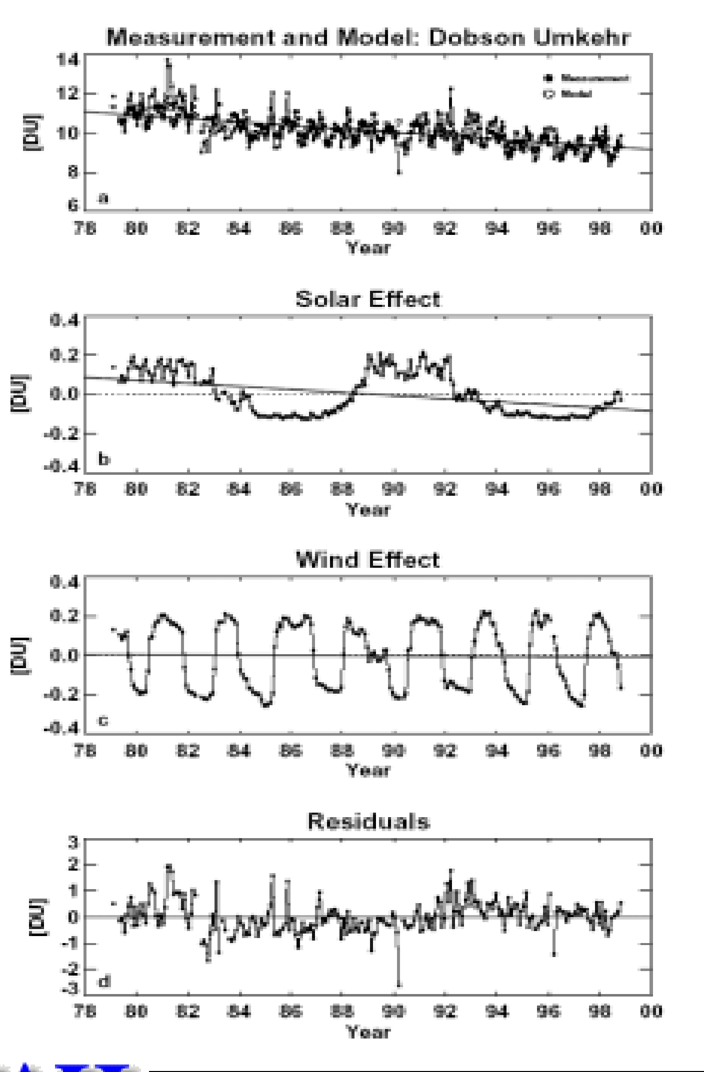


Figure 4. (left) Observations of chlorine partitioning as a function of altitude from an instrument on board the space shuttle [*Zander et al.*, 1996]. (right) Observed vertical profile of the ozone trend at northern midlatitudes [*Harris et al.*, 1998], together with a current model estimate [from *Solomon et al.*, 1997].

These ATMOS SpaceLab-3 observations corroborated by ATMOS on ATLAS 1, 2, & 3.

Solomon, Rev. Geophys., 1999

Statistical Modeling of Measured Ozone Time Series



We understand well how to calculate statistical models of ozone time series that account for the important forcing functions: Many models compute essentially the same trends. Also, several independent measurement systems produce similar ozone trends.

Plenary lecture:
J. Staehelin, Thurs am
D. Brunner, Tues pm
http://www.qos2004.gr/

Newchurch et al., JGR, 2000.

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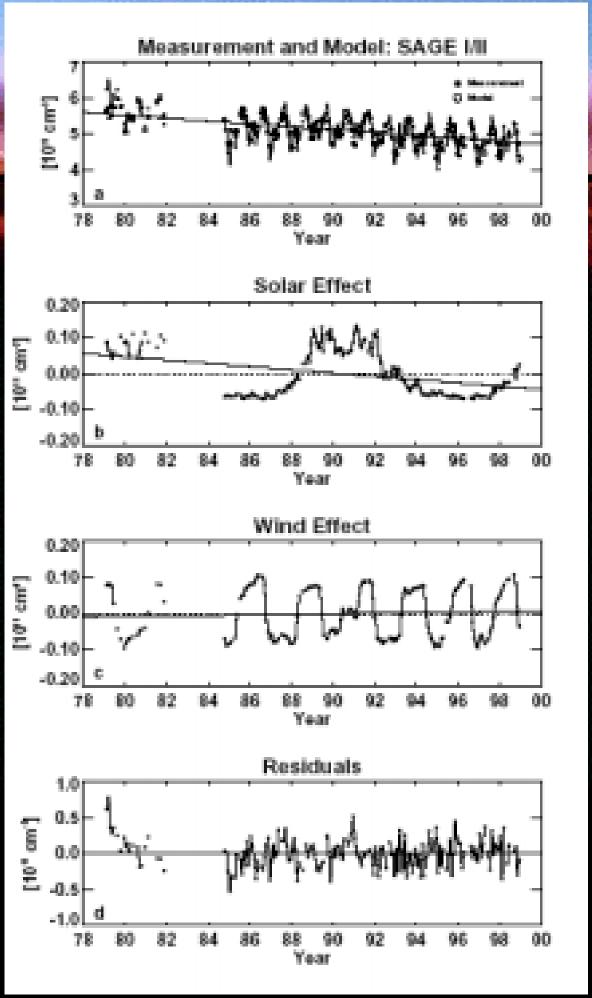
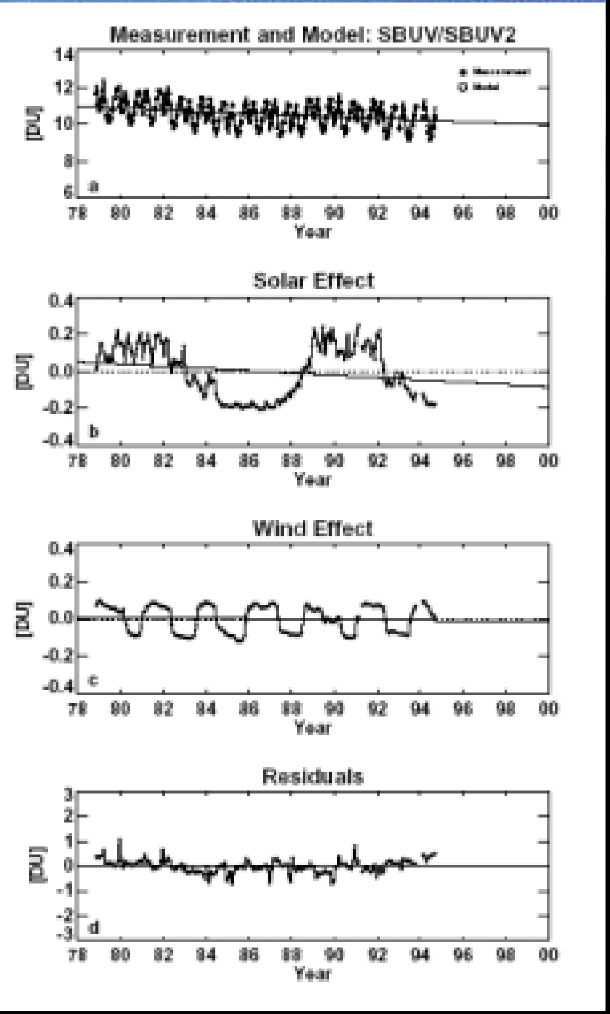
Statistical Modeling of Measured Ozone Time Series



SAGE I and II. Gap in early 1980s, but longer record than SBUV (2).

SBUV and SBUV (2) bridge SAGE I/II gap.



The ozone trend model

$[O3]_t = \mu + \omega t$ + [Seasonal terms] + [QBO periodic terms] + $\gamma\ [F10.7]_t + N_t$

μ is the mean level,

ω is a linear trend coefficient,

the seasonal terms represent the 12-, 6-, 4-, and/or 3-months cosine terms each with a time lag

The QBO periodic terms consist of cosines with time lags to represent QBO signal with periods between 3 and 30 months excluding 12-, 6-, 4-,and/or 3-months terms. The traditional approach of using Singapore winds with a fitted lag produces similar results, but with less precise trend estimates and more fluctuations in the residuals.

$[F10.7]_t$ is the F10.7-cm radio flux density which is used to provide a solar variation proxy.

γ is a solar signal regression coefficient.

Nt is the autocorrelated error term, for which a first order autoregressive process is assumed ($N_t = a_1 N_{t-1} + \varepsilon_t$).

The ε_t residuals, after removing the autoregressive component, $a_1 N_{t-1}$, are the residuals that are used to compute the cumulative sums of residuals.

1 and 2-sigma secular-trend envelope

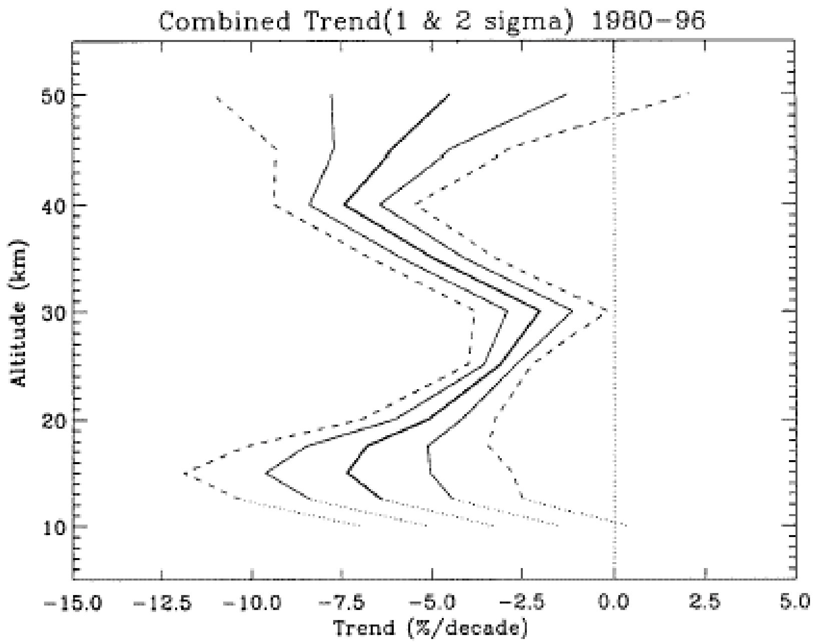


Figure 33. Estimate of mean vertical ozone trends for northern midlatitudes (bold curve) from 1980–1996 based on SAGE I and II, ozone sondes, SBUV, and Umkehr measurements. The combined uncertainties are also shown (1σ, thin solid curve; 2σ, dashed solid curve). The ground-based measurements include those of Table 3 except the Umkehr of Arosa. Reprinted from *Randel et al.* [1999] with permission. Copyright 1999 American Association for the Advancement of Science.

Composite secular trends from Dobson Umkehr, SAGE I/II, and SBUV (/2)
Northern mid-latitudes.

The beginning of the ozone layer recovery begins in about 1997.
Including trends derived from ozonesonde measurements clearly shows a second trend maximum in the lower stratosphere, just below the heart of the ozone layer. This composite include sonde trends in the lower stratosphere.

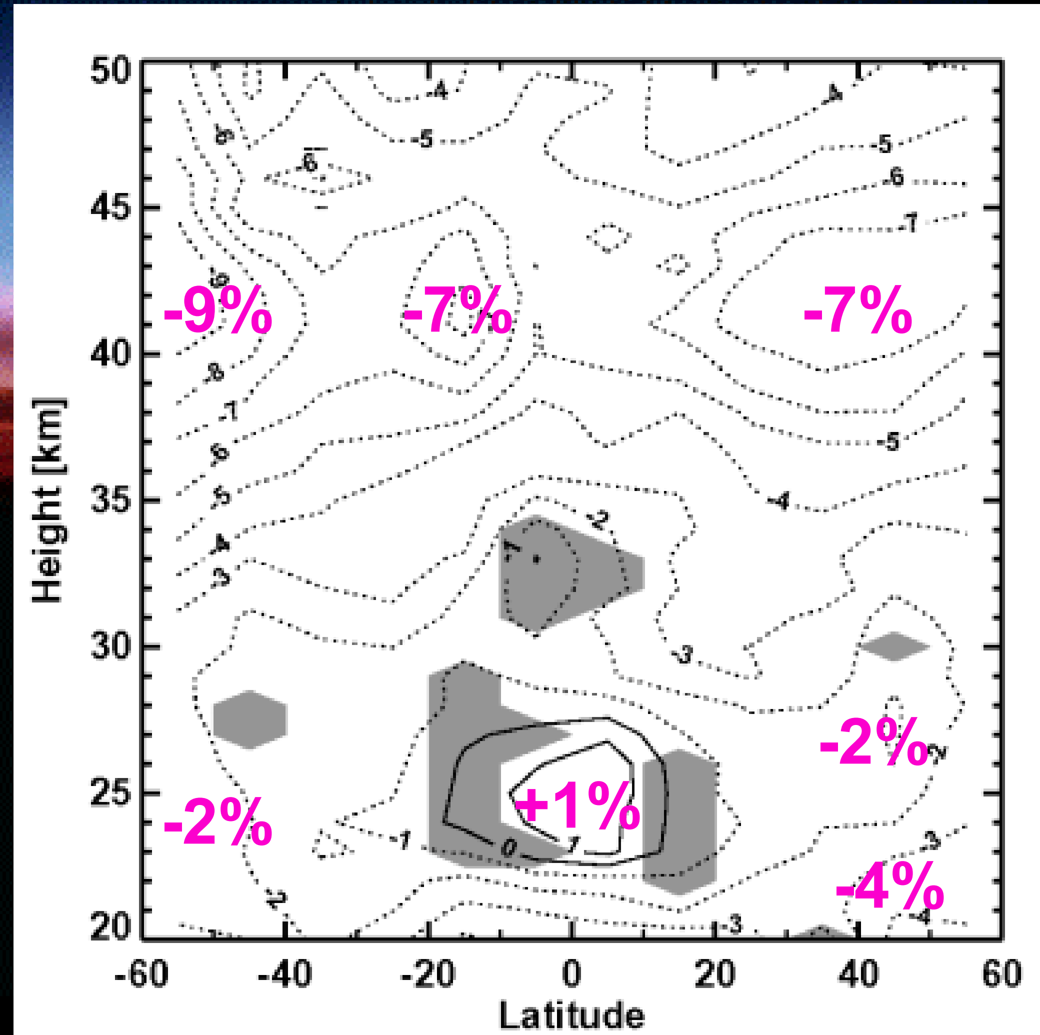
Envelope concept by Rich Stolarski

Staehelin et al., Rev. Geophys, *2001.*
***Figure from* Randel et al., Science, 1999.**

Latitudinal signature of Ozone Trends

Trends calculated from
SAGE I/II observations.
Fingerprints of chlorine
[Solomon, 1999]:

1) Profile shape
2) Latitudinal structure



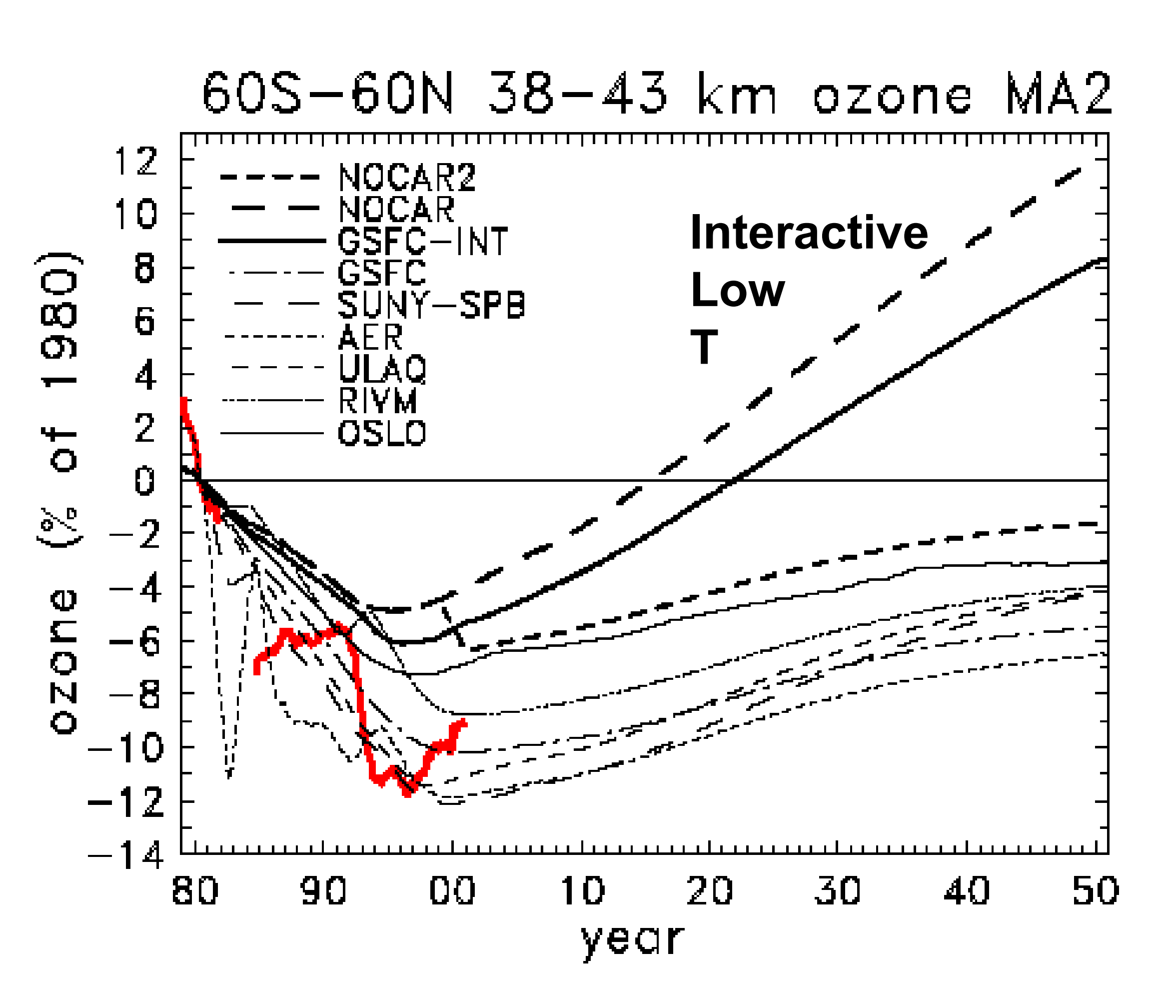
Solomon, Rev Geophys, *1999.*
Newchurch et al., JGR, 2000.
Updated in
Newchurch et al., JGR,, 2003.

What Do We Expect from Here?

9 Predictions

5 Stages of Recovery

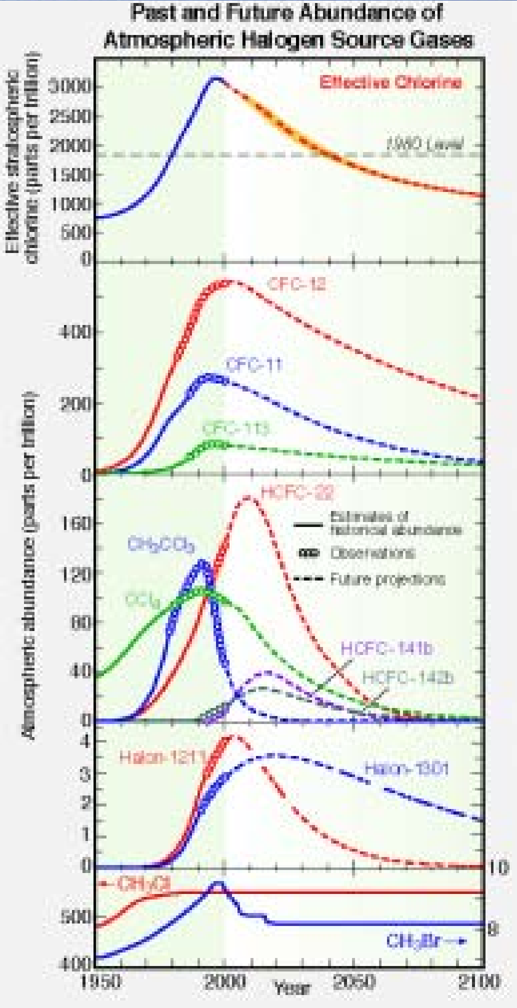
1: Slowdown in loss rate
2: Minimum
3: Increasing ozone
4: Slowdown in increase
5: Full recovery

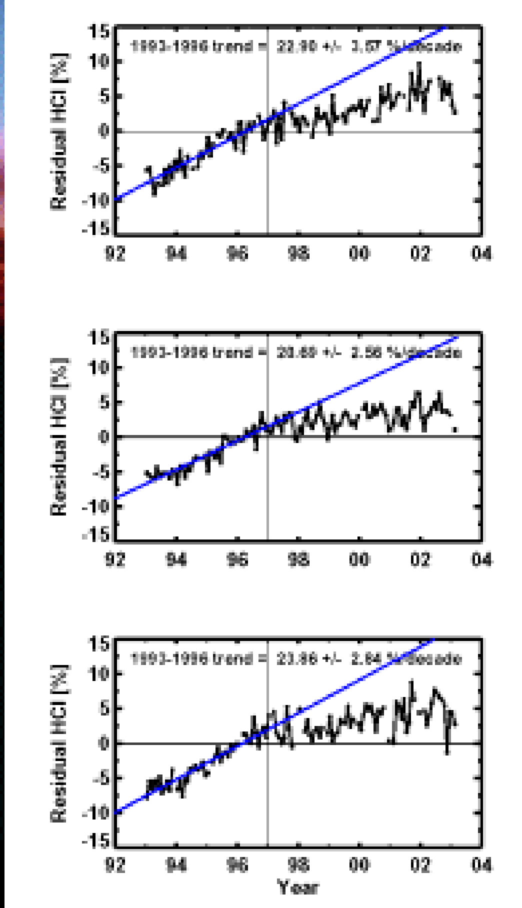


Plenary lecture:
A. Douglass, Fri. pm
M. Chipperfield, Sat am

WMO 2003. Fig 4-43.

Chlorine turning over @ sfc, slowing down @ 40 km



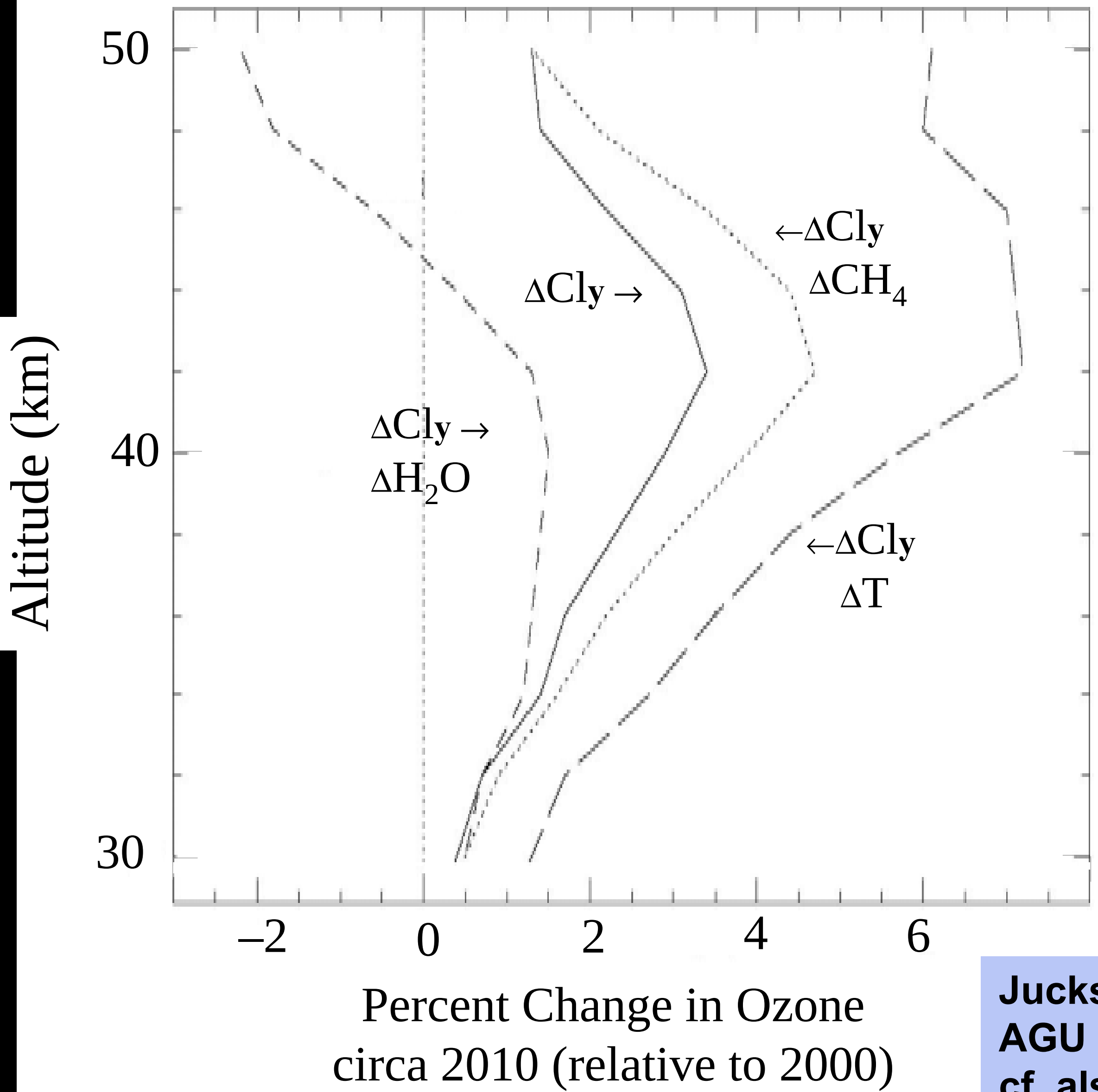


See Russell et al., HALOE constituent trends in 4th public release: HCl, HF, Cl/F, better vertical resolution, comparison to ground trends and emissions.

Newchurch, et al., 2003.

Fahey et al., 2003.
See also Montzka, Cunnold, Remsberg

Sensitivity of Future Changes in Ozone to Cly, H2O, and CH4.



Model Forcings

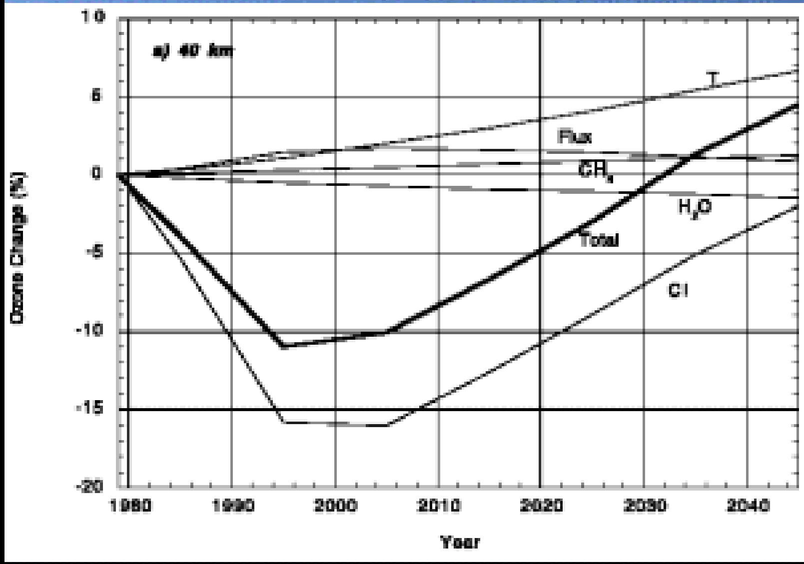
ΔCly	15% ↓
ΔH2O	1.0 ppm ↑
ΔCH4	0.1 ppm ↑
ΔT	~2 K ↓

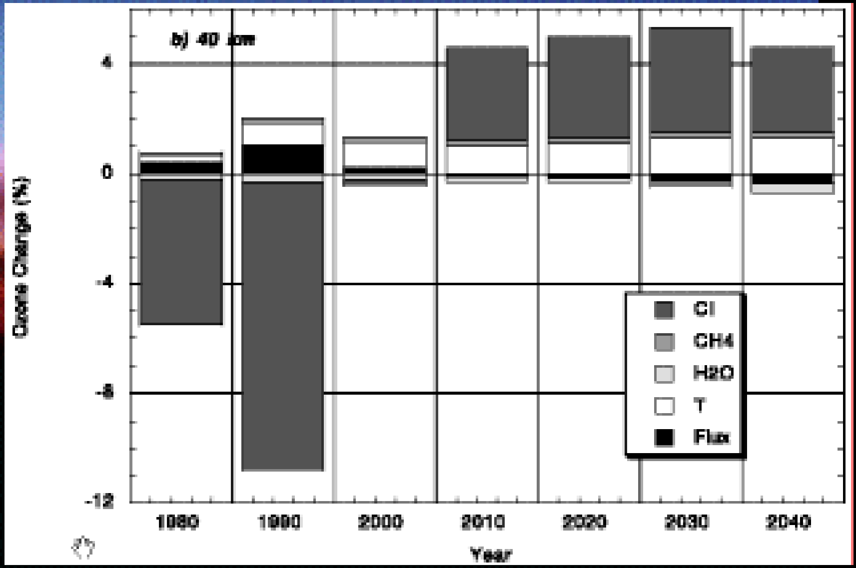
All forcings are based on an extrapolation of present trends. This extrapolation is perhaps most uncertain for H_2O and CH_4.

Plenary lecture: R. Salawitch, Mon am

Jucks and Salawitch, AGU Monograph, 2000.
cf. also [Tabazadeah and Cordero, Atm. Envirn., 2004]: Increasing H_2O delays ozone recovery.

Decadal Evolution of Halogen and Climate Change Influences on Ozone Recovery





Temperature decreases help ozone recovery.
Chlorine effect dominates predicted recovery at 40 km.
CH_4, H_2O, and radiative flux effects are small relative to chlorine.

Shindell, D. T., V. Grewe, JGR, *2002*

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Detecting Difference in Two Linear Slopes

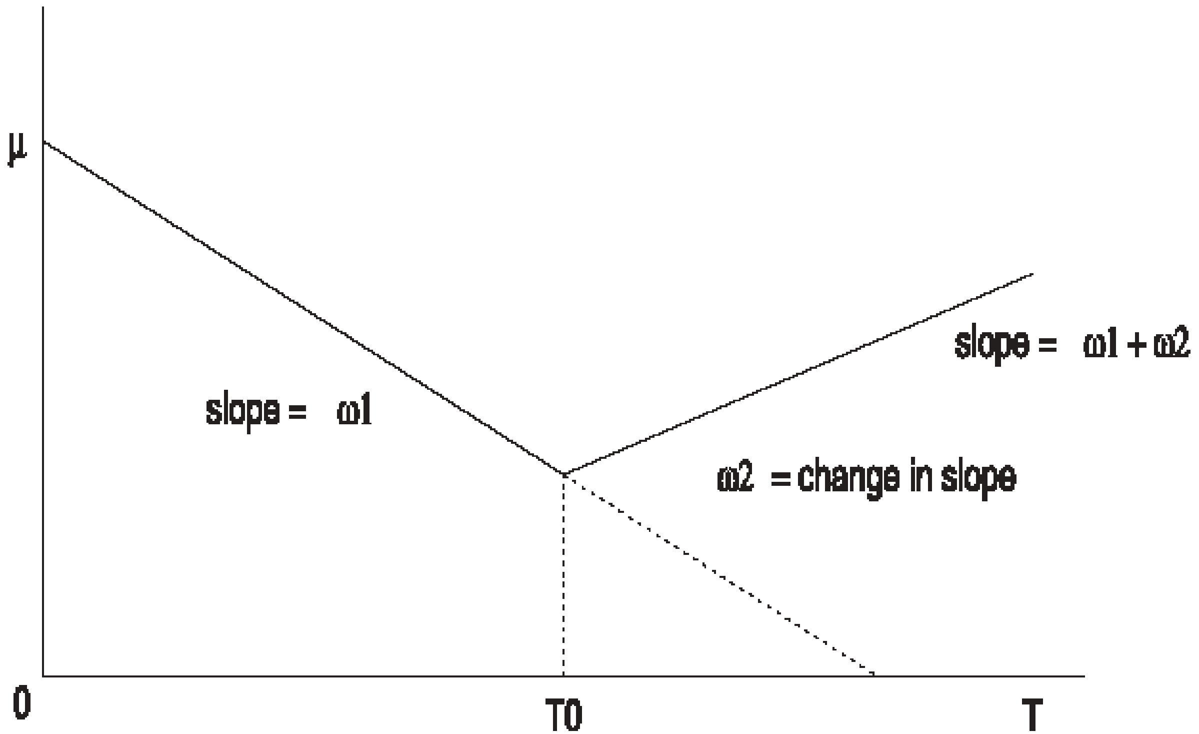

Figure 1. Illustration of linear trend model with change in slope or turnaround at time T_0.

How long will it take to be confident that slope 2 is different from slope 1?

5-30 years in mid latitudes.

20-50 years in the Tropics

Reinsel et al., JGR, 2002.

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Detecting Trend Changes with Cumulative Sum of Residuals

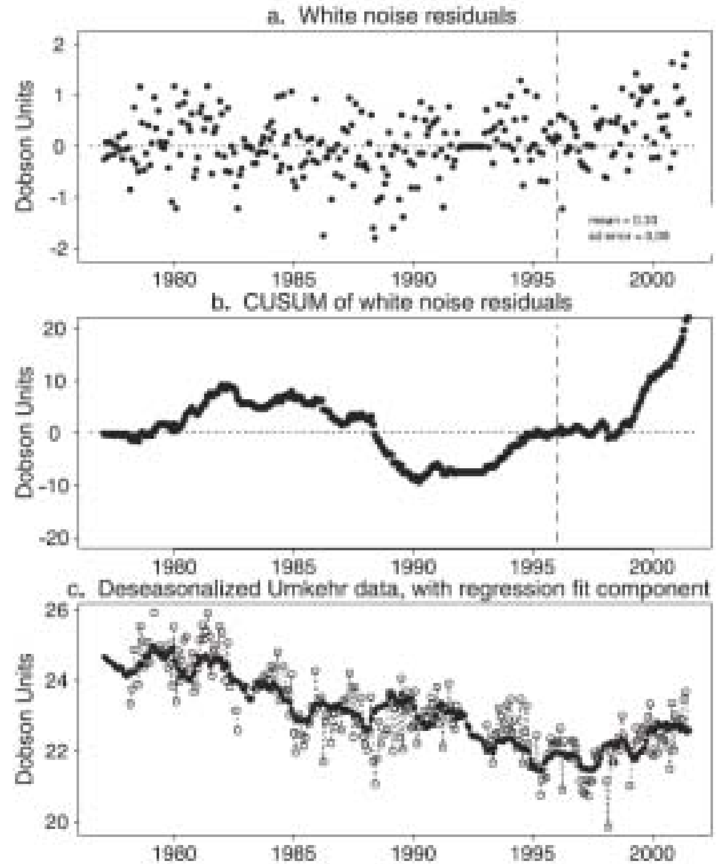

Figure 3. Averages for Umkehr data in layer 7 over the 3 stations, for 1977 to June 2001. (a) Averages of white noise residuals Ξ_t based on fit for 1977–1996; (b) CUSUM of averages of white noise residuals Ξ_t; (c) Deseasonalized aerosol-corrected average Umkehr data (open circles and dashed trace), with average regression fit component including trend (solid dots and trace).

3. Residuals w.r.t. 1977-1996 regression trend line

4. CUSUM
Look at excursions above regression-period variances.

1. Deseasonalized ozone series
2. Fit a trend line 1977-1996.

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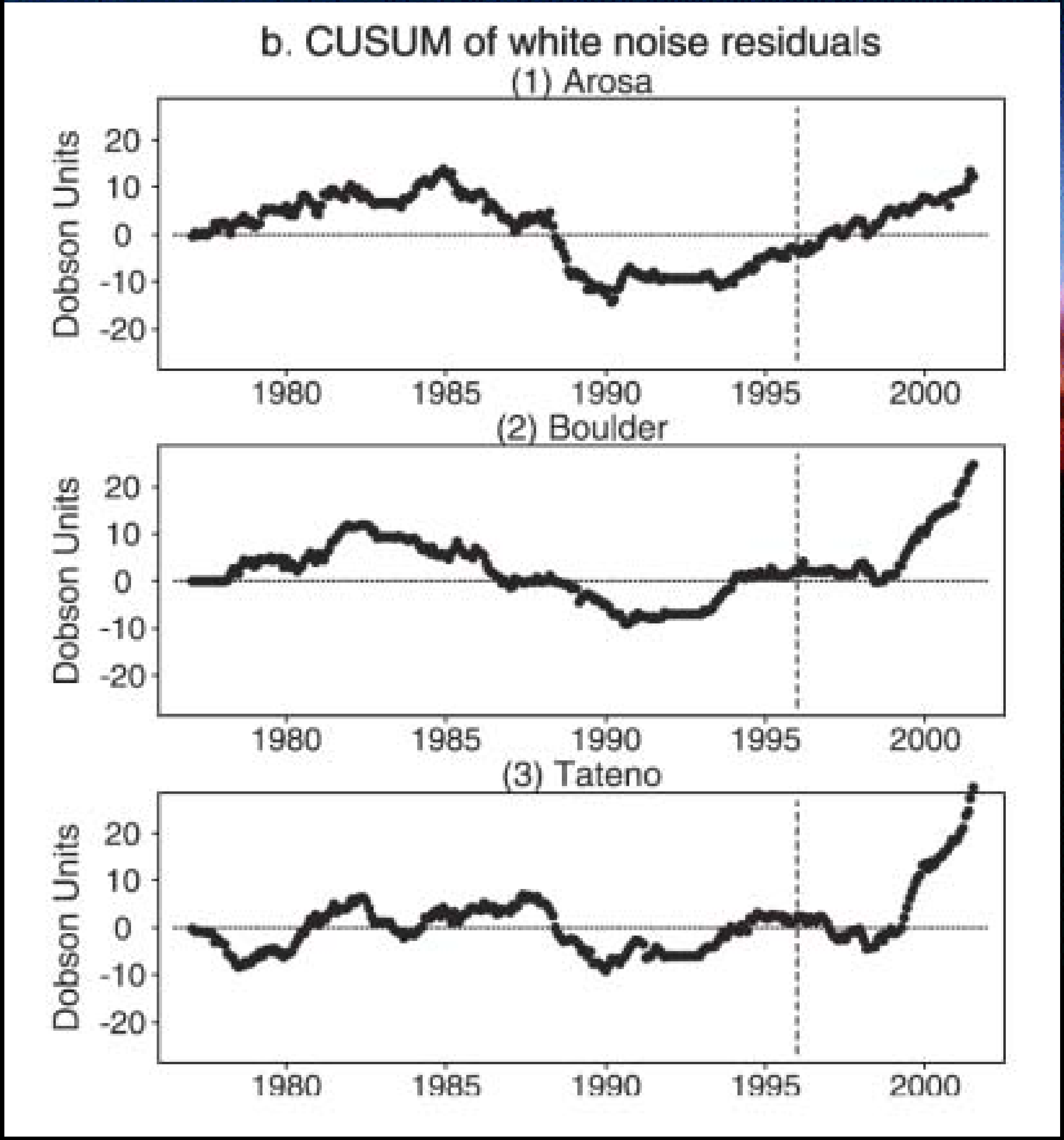
Reinsel GRL, 2002.

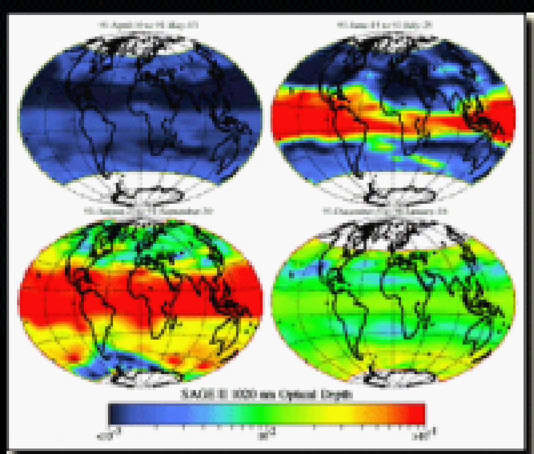
Umkehr CUSUMs

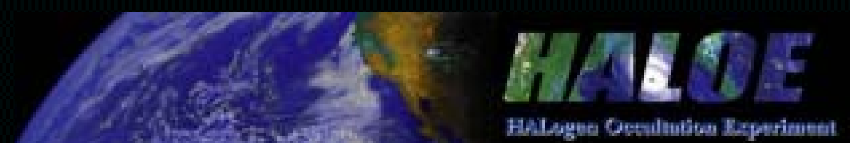


CUSUMs significant at Boulder and Tateno, but not Arosa.

Reinsel, GRL, 2002.

SAGE, SBUV, and HALOE





Plenary lecture:
J. Burrows, Thurs am
P.K. Bhartia, Fri am
A. Richter, Mon am
H. Kelder, Tues am

SAGE I/II and HALOE 35-45km 30-50N

NEWCHURCH ET AL.: FIRST STAGE OF OZONE RECOVERY ACH 12 - 11

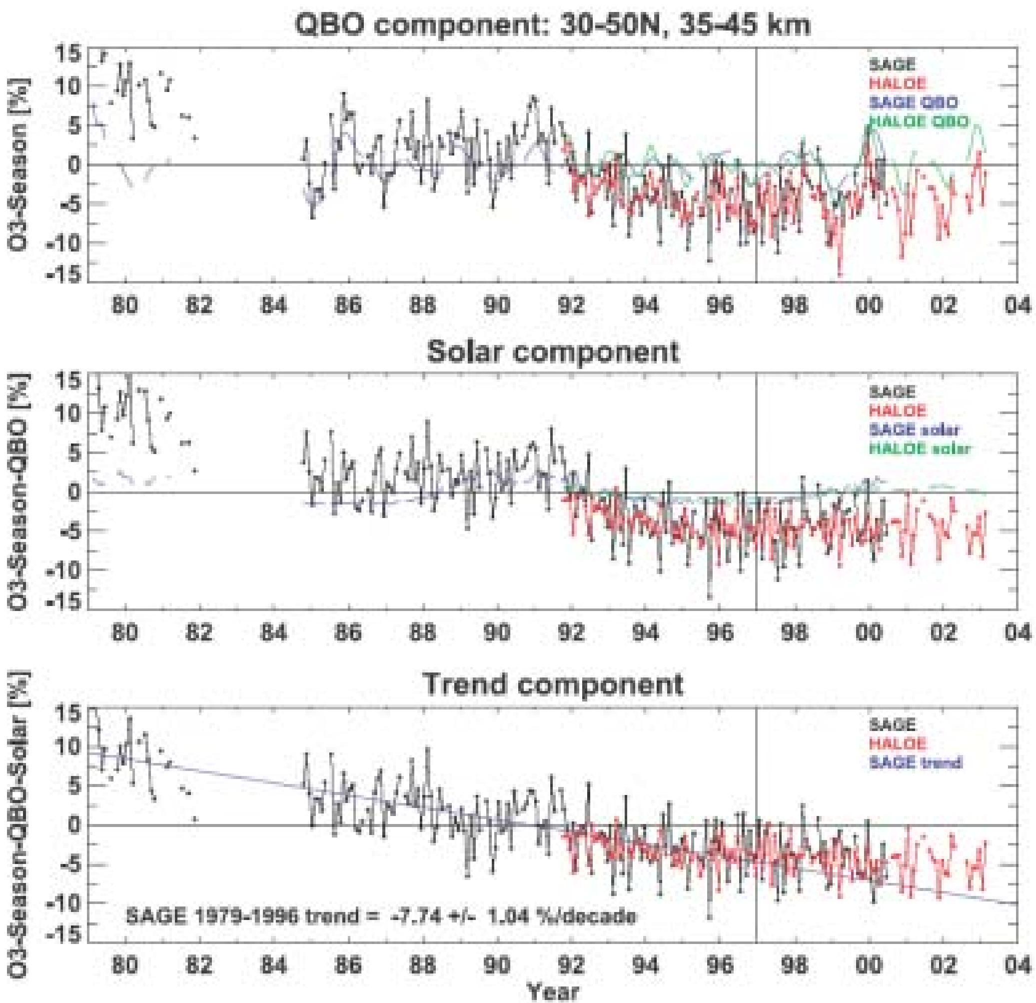


Figure A3. Fitted QBO, solar, and trend components for the SAGE I/II (black dots) and HALOE ozone series (red dots) at 35–45 km, 30–50°N. Top panel: time series of deseasonalized SAGE and HALOE ozone containing QBO, solar, trend, and residual terms (solid lines between symbols) and the fitted harmonic QBO signals (blue line for SAGE QBO and green line for HALOE QBO). Center panel: deseasonalized ozone with the QBO signal removed (solid line between symbols) and the fitted F10.7 cm flux solar signal (blue line for SAGE and green line for HALOE). Bottom panel: deseasonalized ozone with both the QBO and solar signals removed (i.e., only trend and residual terms remain; solid line between symbols) and the fitted linear trend (blue line for SAGE 1979–1996 observations).

Ozone time series with seasonal cycles removed showing the QBO signal in the ozone data.

Ozone time series with seasonal cycles and the QBO signal removed showing the solar component in the ozone data.

Ozone time series with seasonal cycles, QBO, and solar signal removed leaving the secular trend 1979-1997, projected to 2004.

Newchurch, et al, JGR, 2003.

SAGE I/II and HALOE 35-45km CUSUMS

SAGE observations

Measurements above projected trend

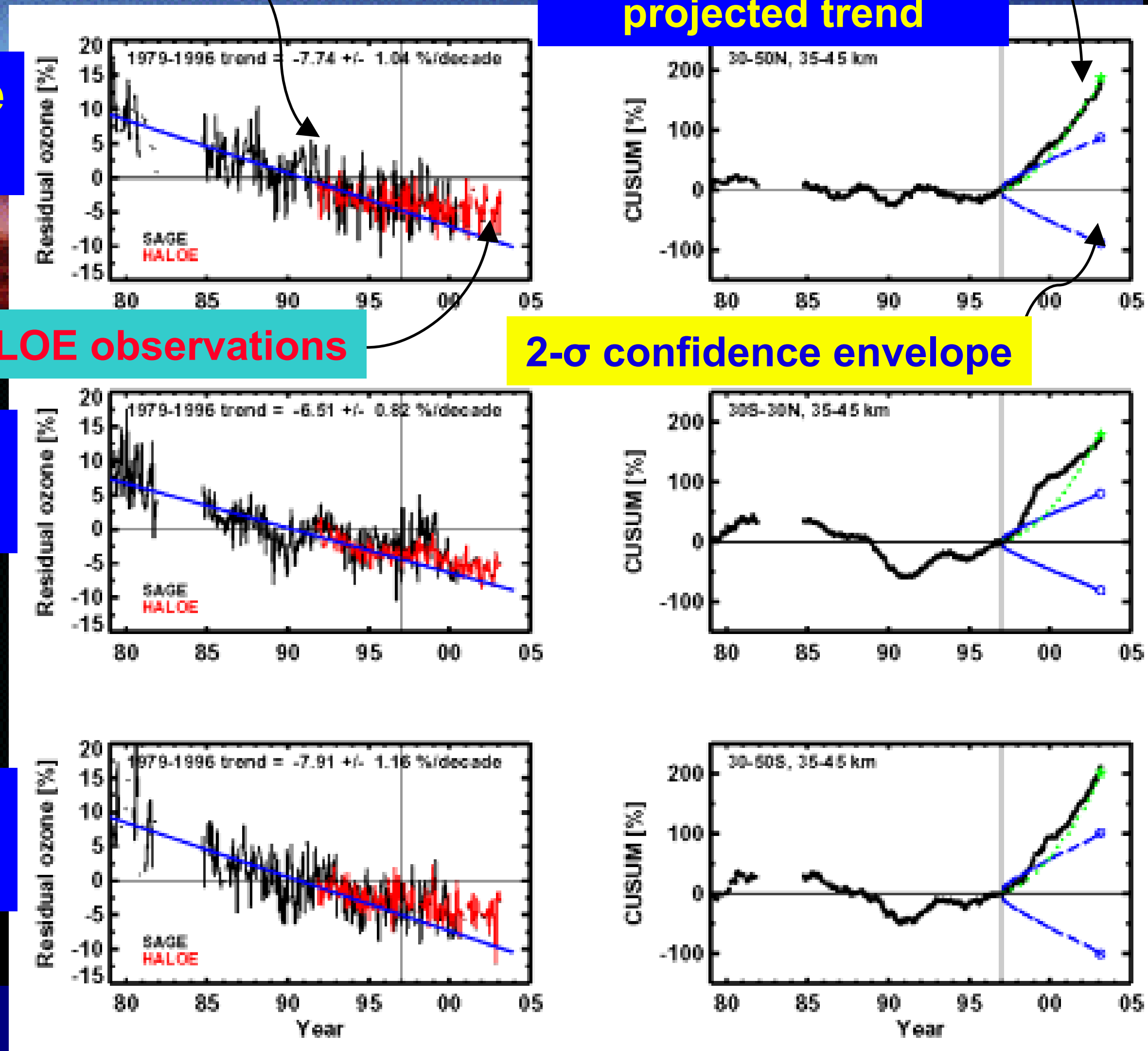
Northern Midlatitude Upper Stratosphere

HALOE observations

2-σ confidence envelope

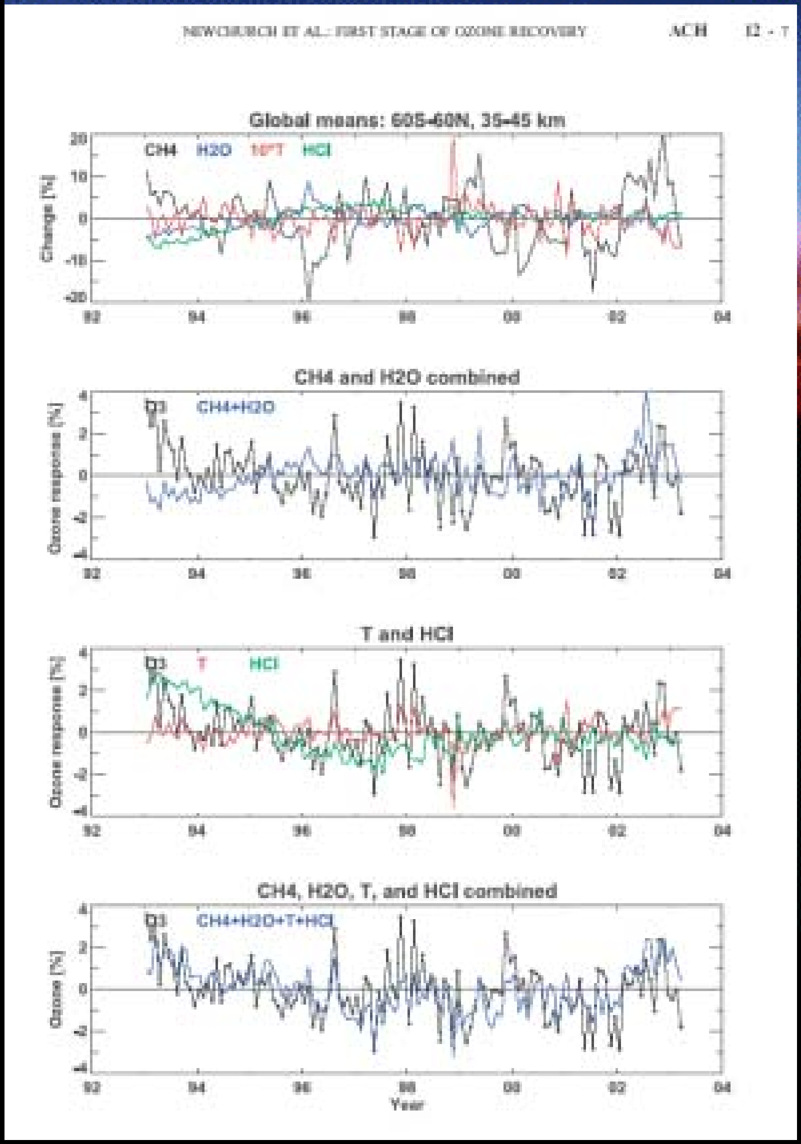
Tropics Upper Stratosphere

Southern Midlatitude Upper Stratosphere



Newchurch, et al, JGR, 2003.

Statistical Attribution



See Remsberg and Deaver, solar cycle and QBO components of mesopshere and US trends in O3 and T.

CH_4, H_2O, T, and HCl residuals plus trend.

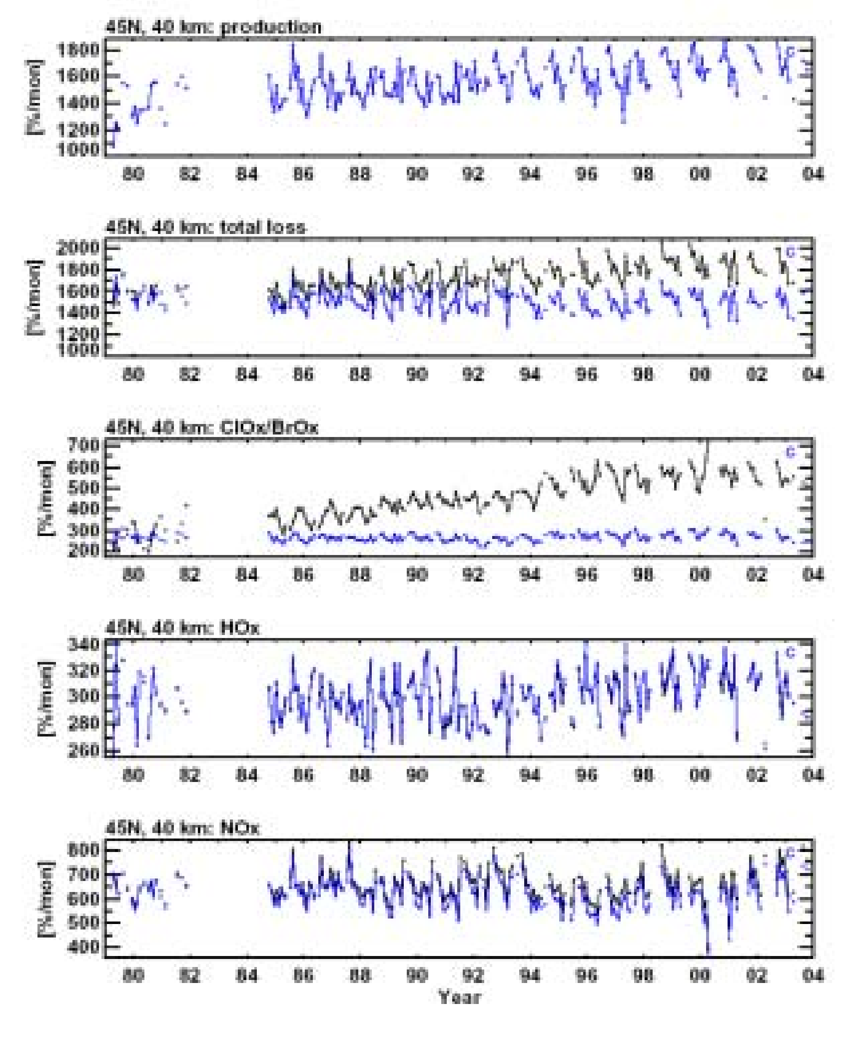
CH_4 and H_2O impact on ozone empirically estimated from regression (blue).
O_3 residuals plus trend (black).

T (red) and HCl (green) influence on ozone.
O_3 residuals plus trend (black).

O3 residuals plus trend (black).
CH_4, H_2O, T, and HCl impact on O_3.

Newchurch, et al., 2003.

Photochemical-model Rates 40 km 45N



Total Production rate %/month

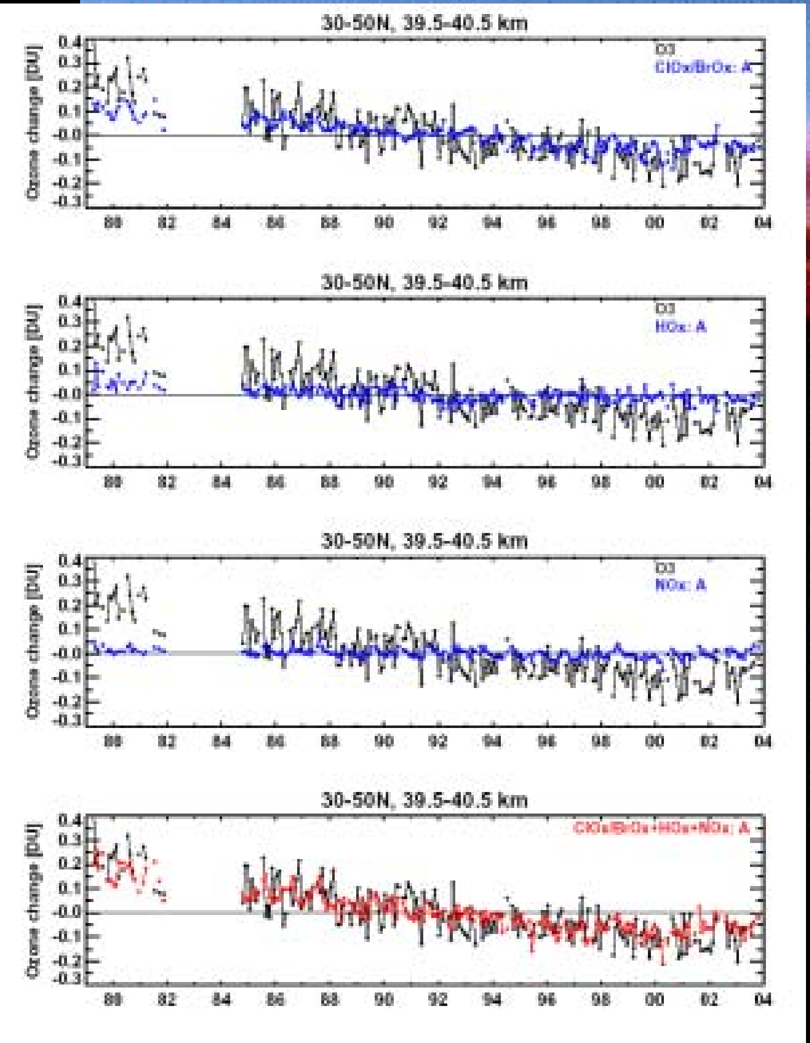
Total Loss Rate with measured ClO (black)
With constant 1979 halogen levels (blue).
Difference is attributable to halogen loss.

Halogen Loss Rate with measured ClO (black)
With constant 1979 halogen levels (blue).
Difference is attributable to halogen loss.

HOx loss rate with evolving HOx (black)
With constant HOx (blue)
Small difference indicates little HOx attribution

NOx loss rate with evolving HOx (black)
With constant NOx (blue)
Small difference indicates small NOx attribution.

Regression of Model Loss Rates against Ozone (40 km, 30-50N)



Residual ozone (black).
Ozone residual from halogen rxns (blue).

Ozone residual from HO_x rxns (blue)

Ozone residual from NO_x rxns (blue)

Ozone residual from combined ClO_x, HO_x, NO_x rxns (red).

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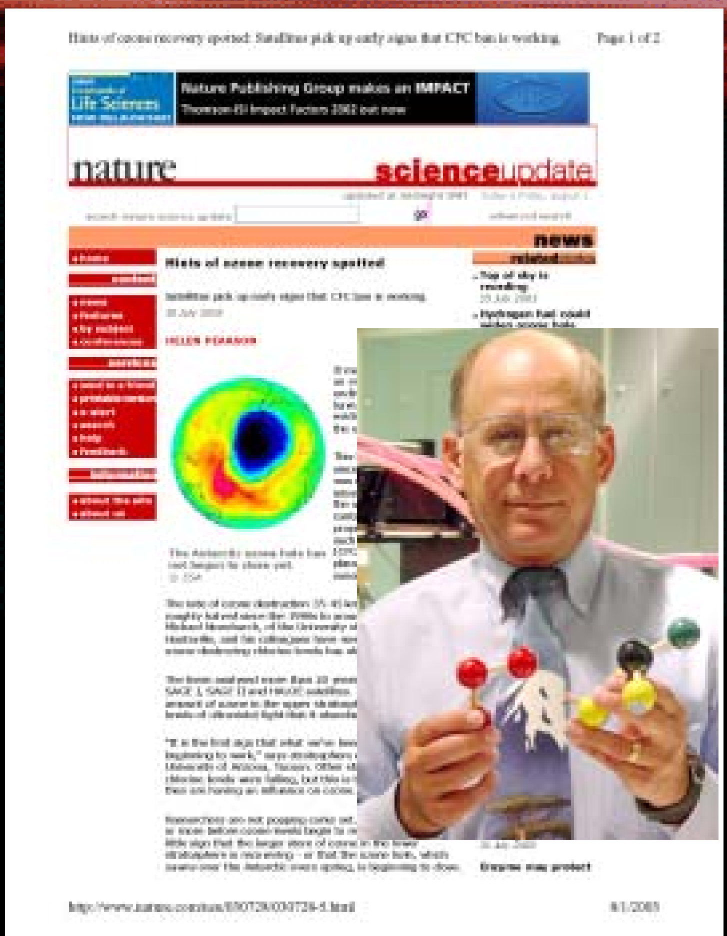
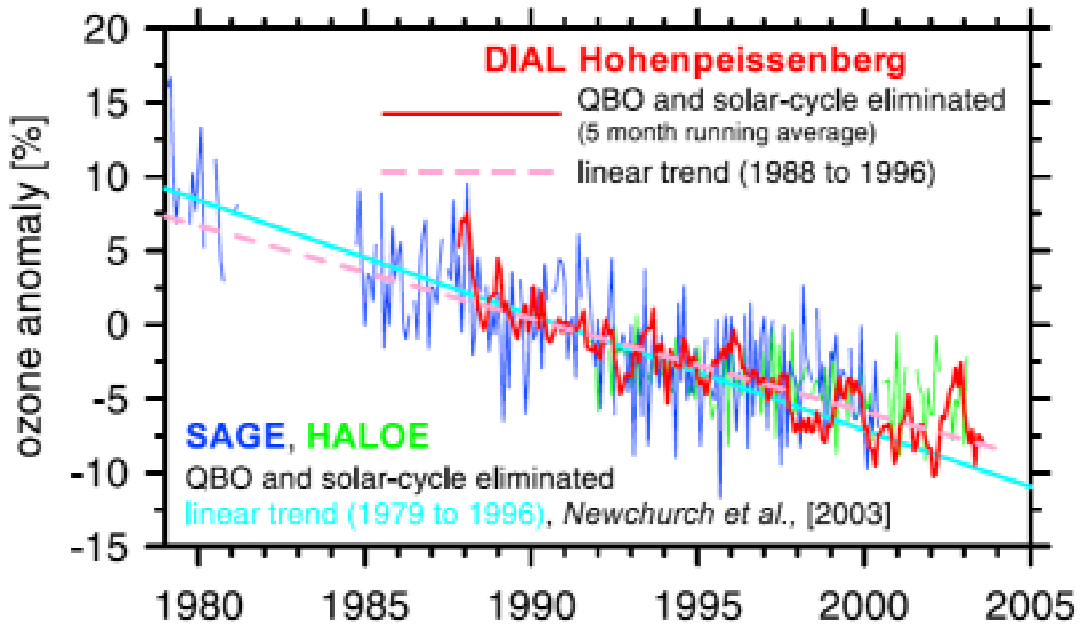
Presented at the National Press Club
Washington, D.C. July 29, 2003
>100 news stories
Live TV, radio interviews
All time high hit AGU, #1 2003 AAAS EurekAlert
40k hits (2x #2 story)
Invited to Gordon Research Conf., AGU 2003,
Quadrennial Ozone Symposium 2004



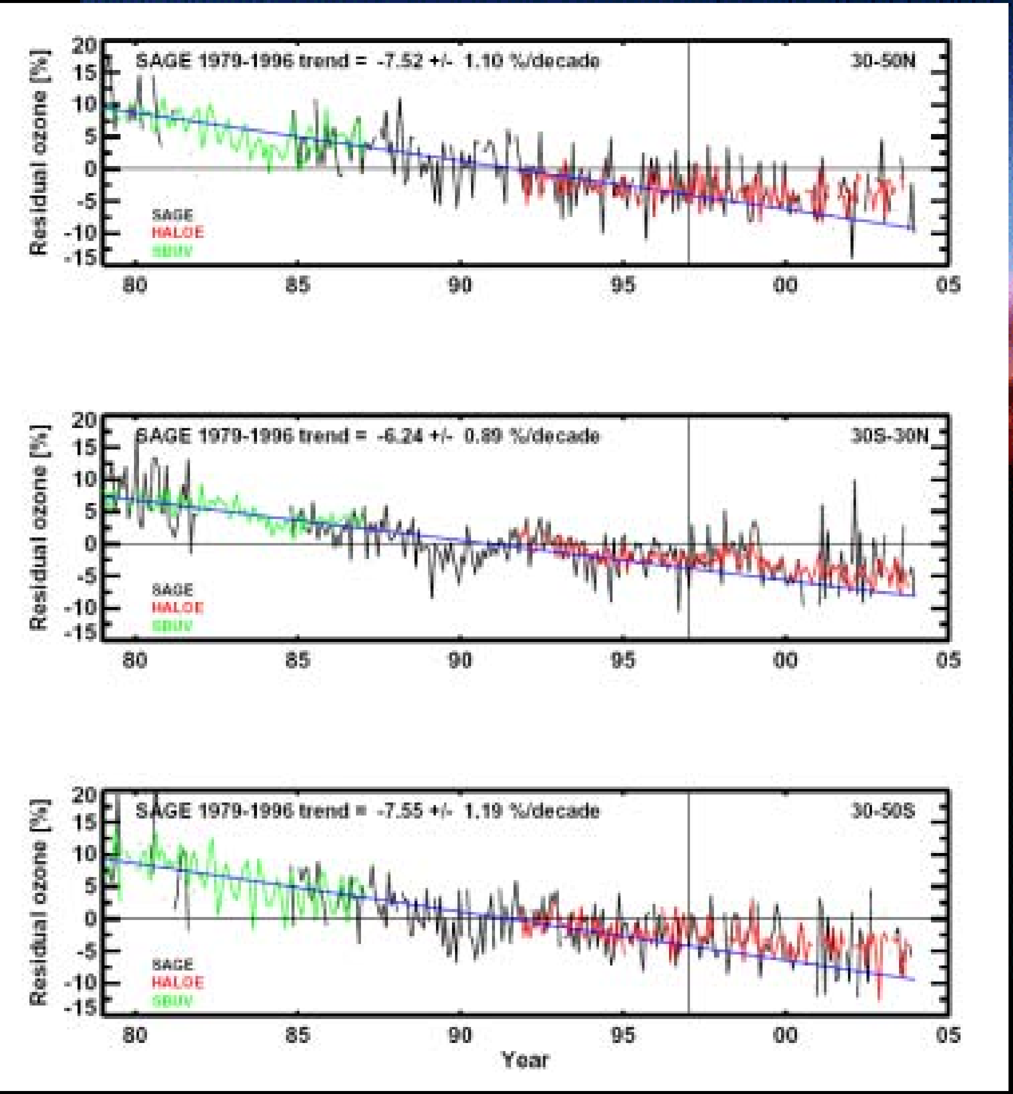
Lidar Observations Corroborate Satellite data Attribution Questioned: Cl or Solar?

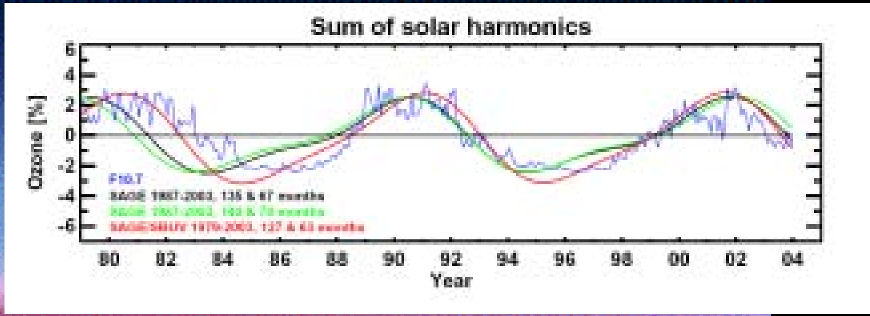


Steinbrecht et al. suggested that it may be impossible to distinguish between a solar- cycle effect and a chlorine response in ozone. Length of record is crucial. SAGE I credible?

Steinbrecht et al., JGR, *2003.*

Response to the Questions



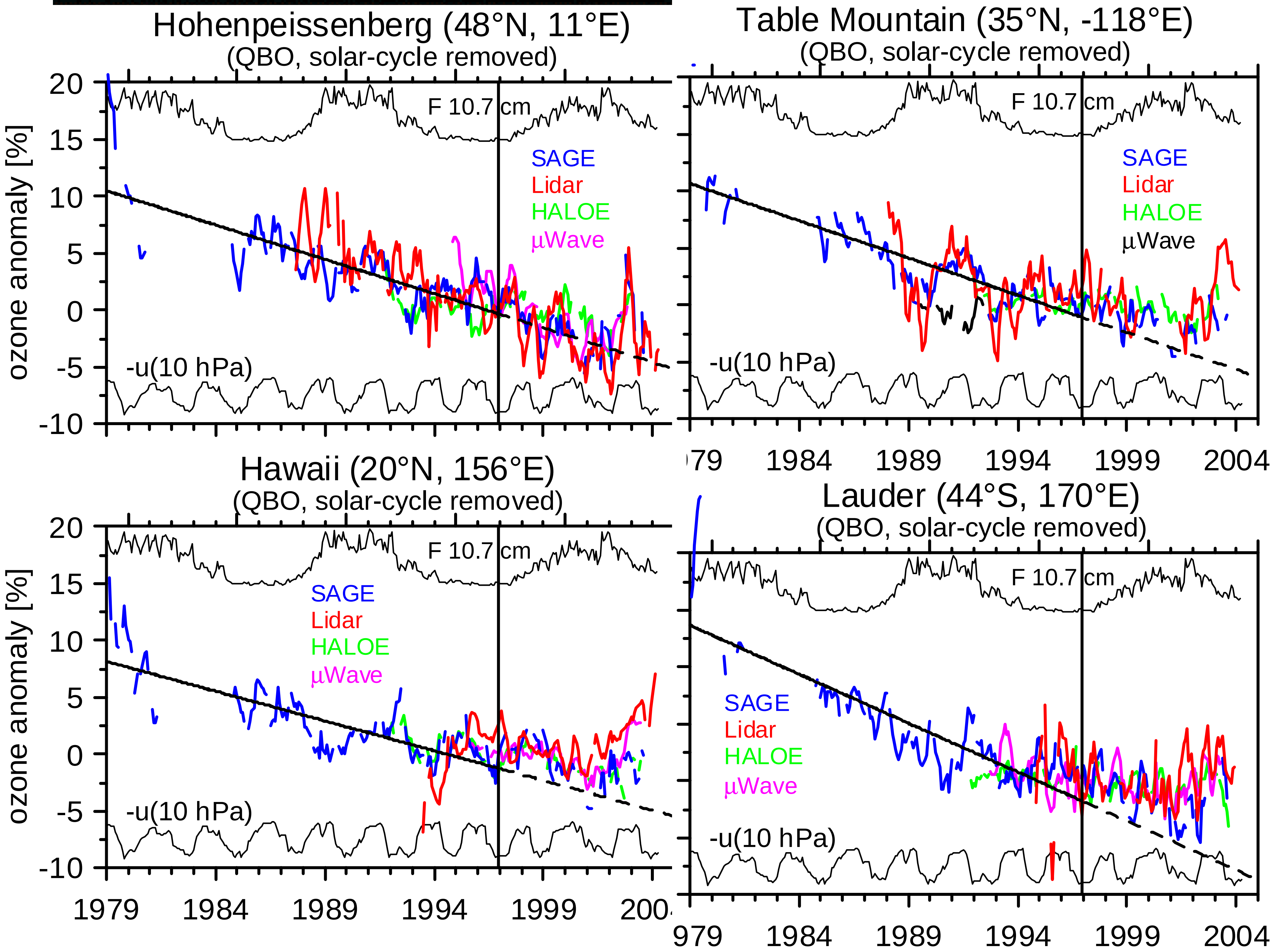


Length of record is indeed crucial: SAGE I/II, SBUV, HALOE = 25 years = 2 solar cycles. Solar harmonics from 25 yr period .ne. harmonics from lidar period. Longer time-series fits solar observations better.

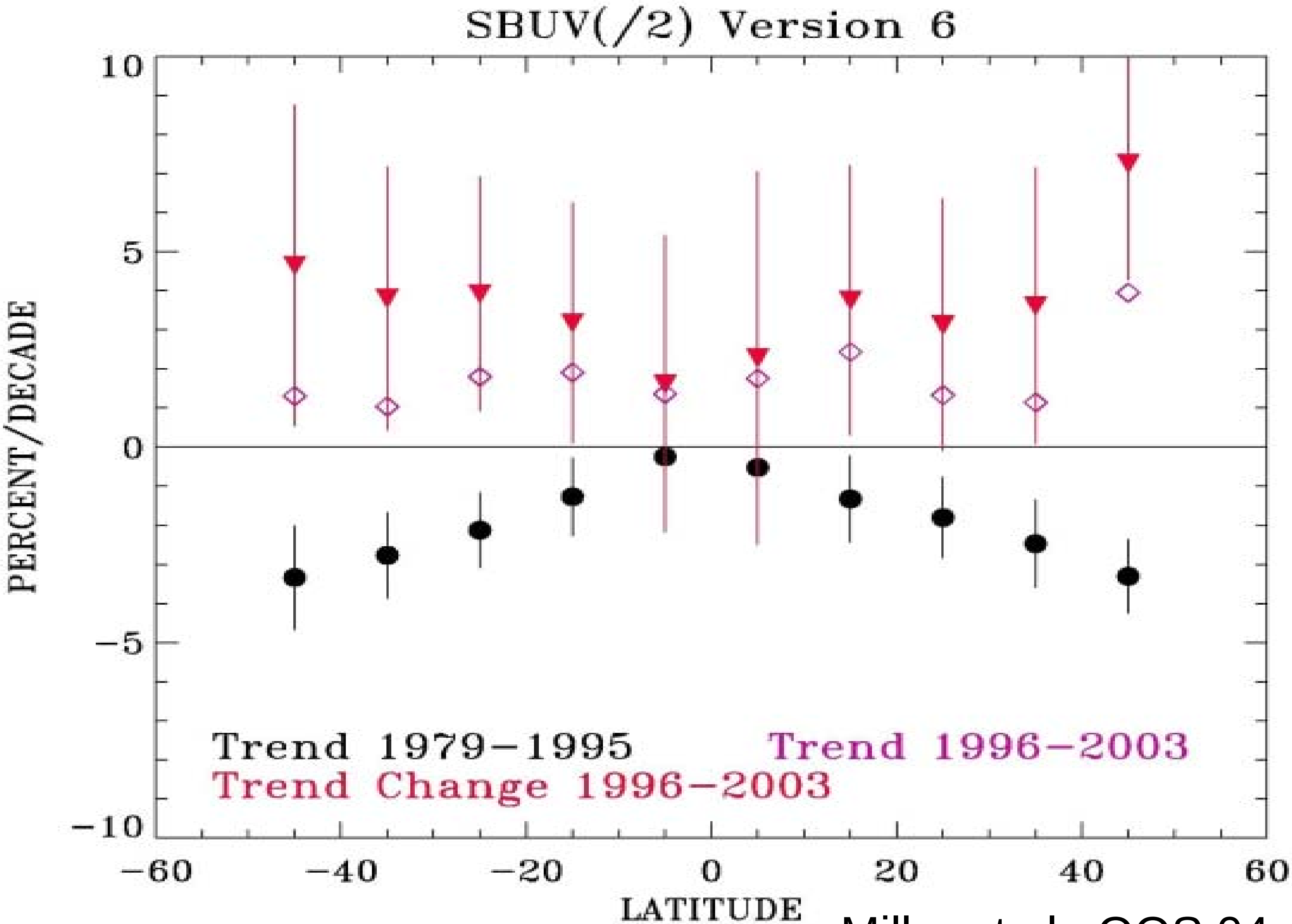
Better solar fit removes more variance from ozone time series and improves significance of the CUSUMs.

SBUV clearly corroborates accuracy of the SAGE I ozone observations (cf. also Harris et al. IOC/SPARC, 1998, Newchurch et al., 2000 for corroboration with Umkehr measurements).

Cunnold, et al., in press, JGR, 2004.

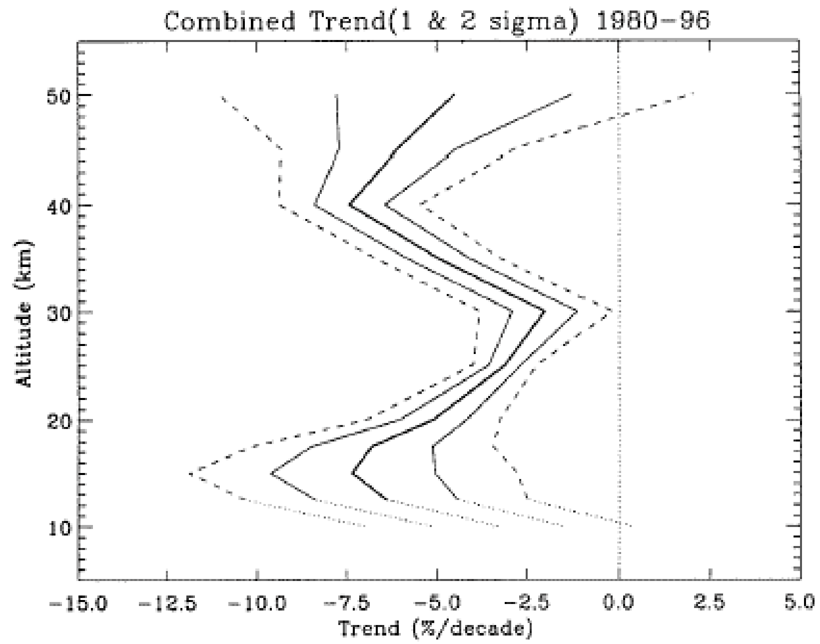


Hohenpeissenberg (48°N, 11°E)
(QBO, solar-cycle removed)
Table Mountain (35°N, -118°E)
(QBO, solar-cycle removed)
Hawaii (20°N, 156°E)
(QBO, solar-cycle removed)
Lauder (44°S, 170°E)
(QBO, solar-cycle removed)
F 10.7 cm
SAGE
Lidar
HALOE
μWave
-u(10 hPa)
ozone anomaly [%]
20
15
10
5
0
-5
-10
1979
1984
1989
1994
1999
2004



Miller et al., QOS 04

Lower Stratosphere Trends



Staehelin et al., Rev Geophys, *2001.*
***Figure from* Randel et al., Science, 1999.**

Including trends derived from ozonesonde measurements clearly shows a second trend maximum in the lower stratosphere, just below the heart of the ozone layer.

Envelope of multiple sensor observations developed by Rich Stolarski

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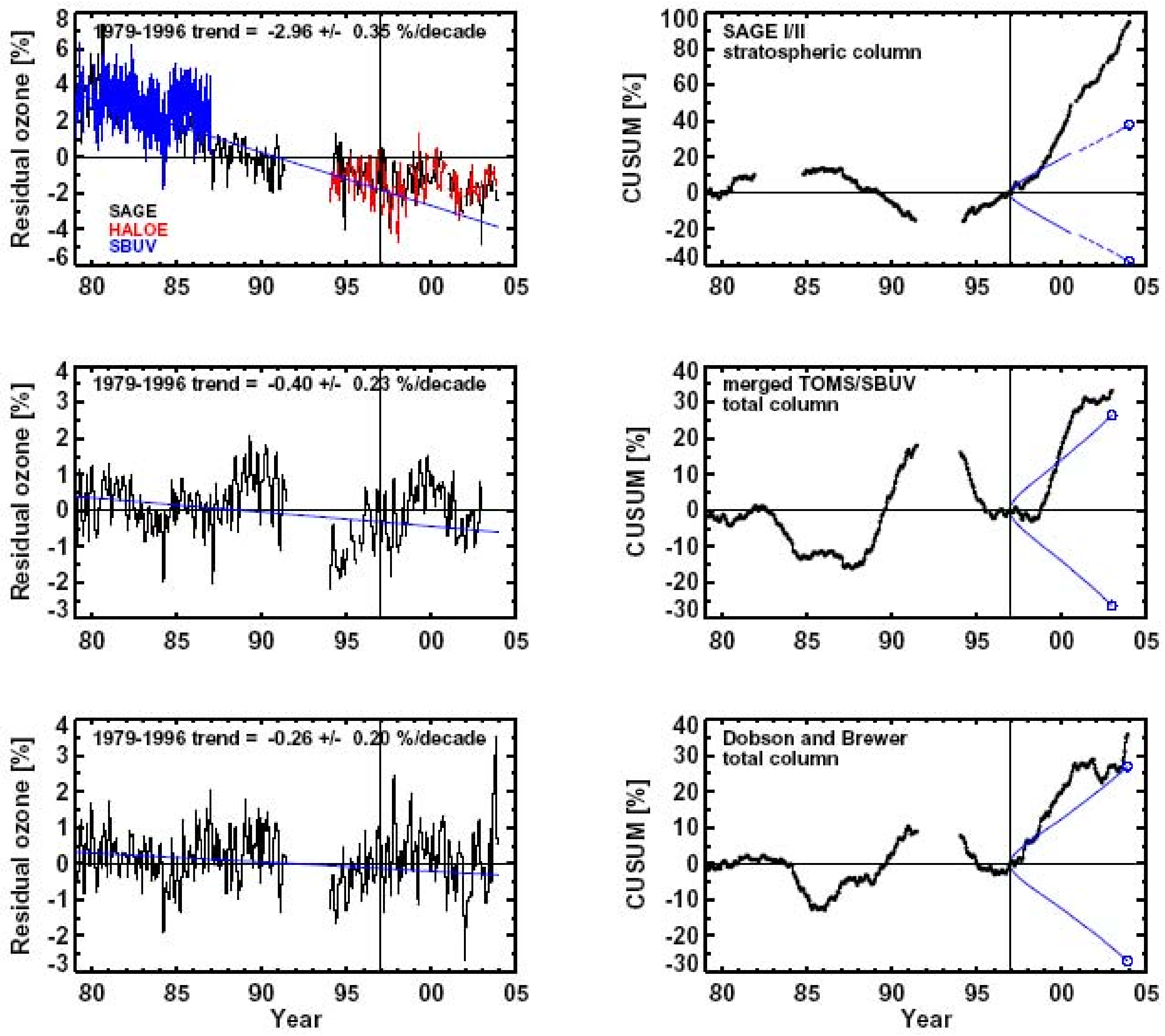
1[ST] Stage Ozone Recovery Stratospheric Column Tropics

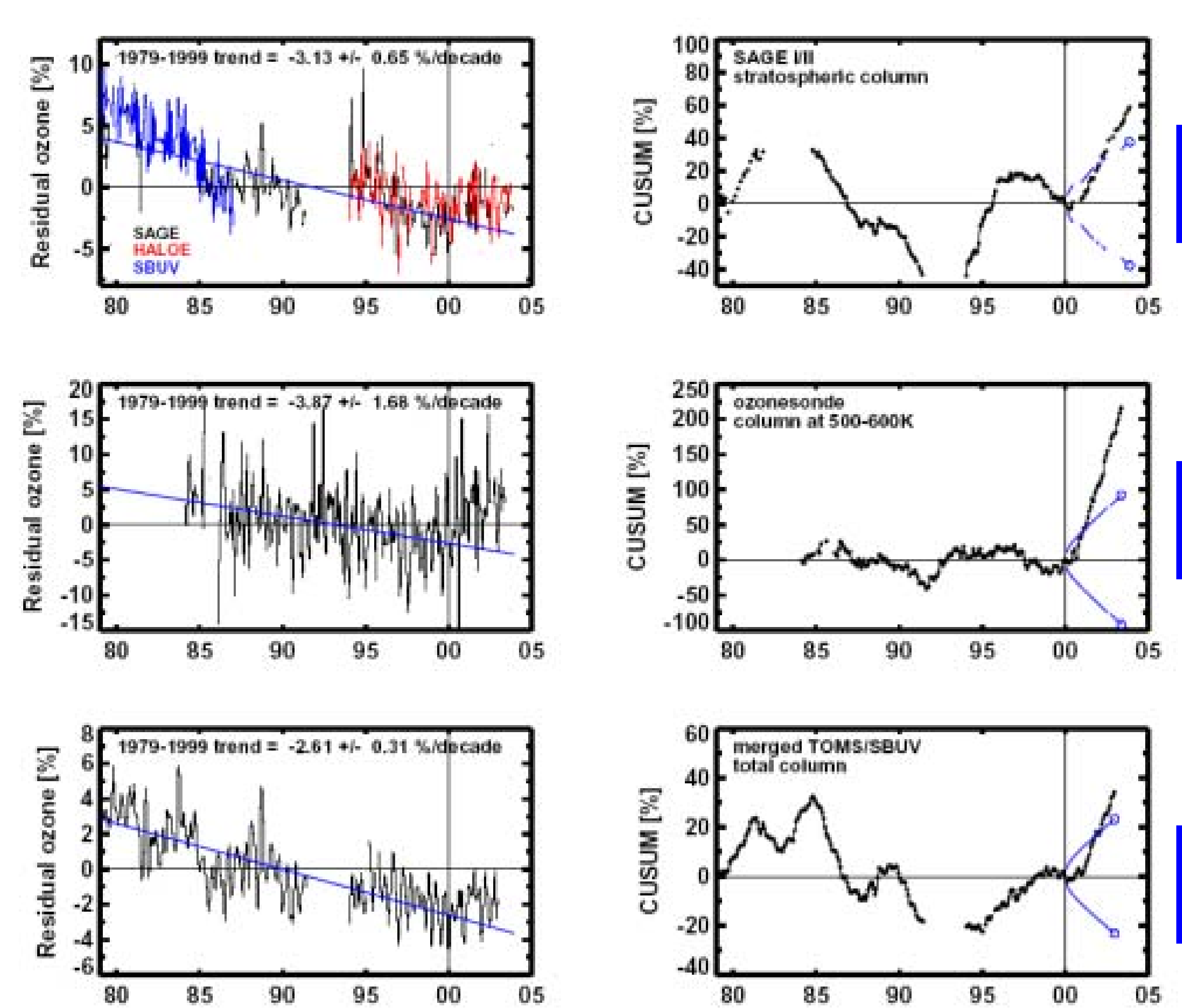


SAGE I/II Stratospheric Column

TOMS/SBUV Total Column

Dobson & Brewer Total Column

1^{ST} Stage Ozone Recovery Stratospheric Column SH

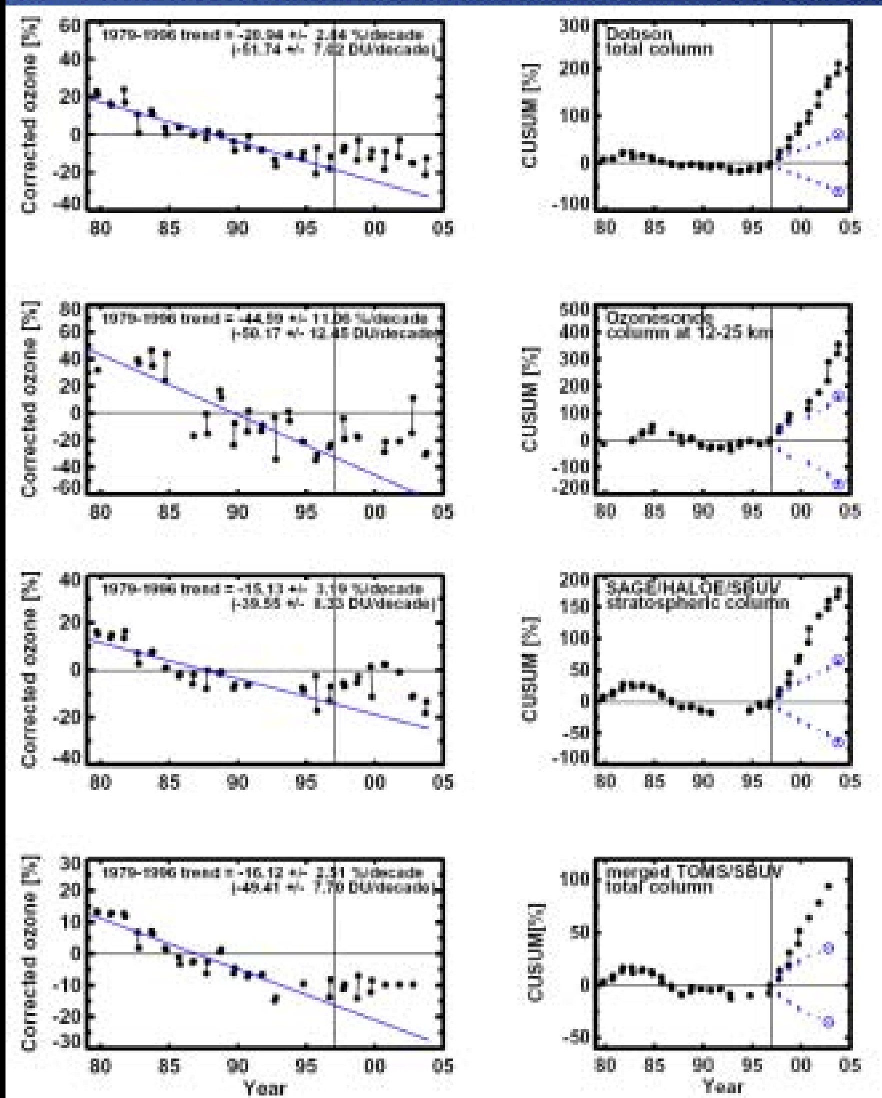


SAGE I/II Stratospheric Column

Ozonesonde Column 500-600 K

Merged TOMS/SBUV Total Column

1ST Stage Ozone Recovery Stratospheric Column 60-70° South Filtered for Temperature Effects



Dobson Total Column: Vernadsky and Syowa

Ozonesonde Column 12-25 km at Syowa

SAGE/HALOE/SBUV Stratospheric Column

Merged TOMS/SBUV Total Column

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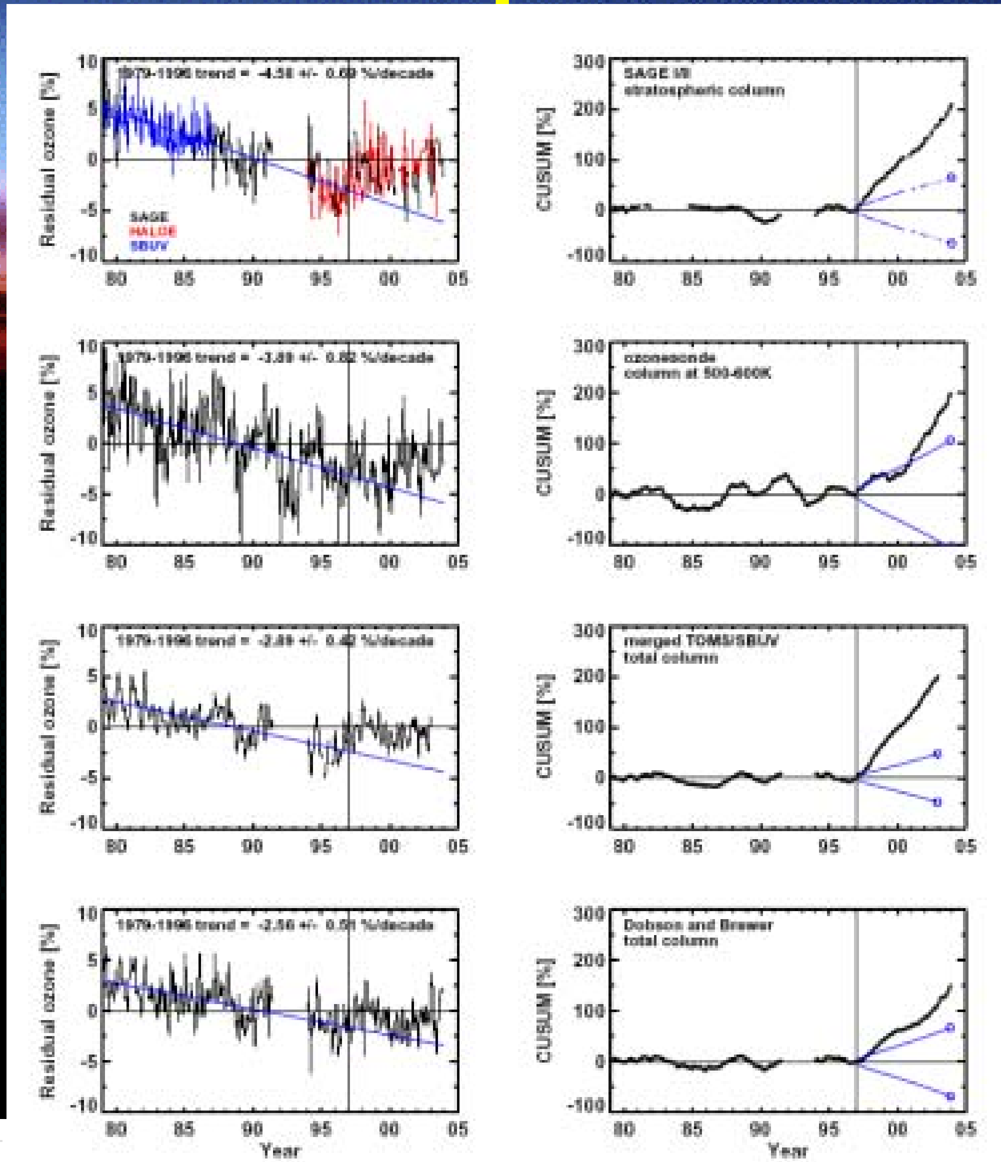
Yang et al, *in prep*, 2004.

1^{ST} Stage Ozone Recovery Stratospheric Column NH



SAGE I/II Stratospheric Column

Ozonesonde Column 500-600 K

Merged TOMS/SBUV Total Column

Dobson & Brewer Total Column

Attribution of Total Column Ozone

Attribution of Lower Stratospheric ozone requires separation of dynamical from chemical effects. Two approaches:

1) First remove dynamic effects by regression of proxies (E-P Flux, PV, Geopotential Height, AO, etc.) See Logan analysis. Then apply production/loss modeling as in upper stratosphere.

2) Analyze trends in dynamical coordinate system: See

- Bodeker, trend analysis in equivalent-latitude coordinate.
- Jing et al., PV mapping and contour advection for UTLS flux.
- Dunkerton, Effect of convective transport during the monsoon in 3 different areas. Satellite sampling bias.
- Harvey et al., Effect of anticyclones on ozone distribution: are low-ozone pockets significant for trend analysis? Sampling?
- Anderson et al., more accurate SAGE II characterization of interannual var. Better trends?
- Wang, Better SAGE II vertical resolution in UT/LS improves data quality for all studies.
- Wang et al., Trends in UT/LS with improved vertical-resolution SAGE II data.
- Weisenstein, Model aerosols to diagnose dynamical causes of interannual variability: Tropical convection, high-latitude synoptics, mid-latitude complex chemistry/temperature interactions.

Tremendous Effort by Ozone Community

25 yrs Stratospheric ballooning (Europe, Canada, USA)
+ Space Lab-3 ATMOS (1985)
+ ATLAS 1, 2, 3 (1992,3,4: ATMOS, MAS, SSBUV, SUSIM)
+ 30 yrs laboratory kinetics measurements
+ 30 yrs photochemical modeling
+ NASA, ESA, Japanese, Canada satellites (BUV, SBUV, SAGE I/II, TOMS, UARS, ADEOS, GOME, ACE, ENVISAT et al.)
+ 50 yrs Ground-based RS: Dobson/Umkehr, many others
+ 20 yrs Ground-based in situ CFC & HCFC obs
+ Lower Stratospheric aircraft obs (ER2 campaigns)
+ 1000s of scientists thoughts and analyses

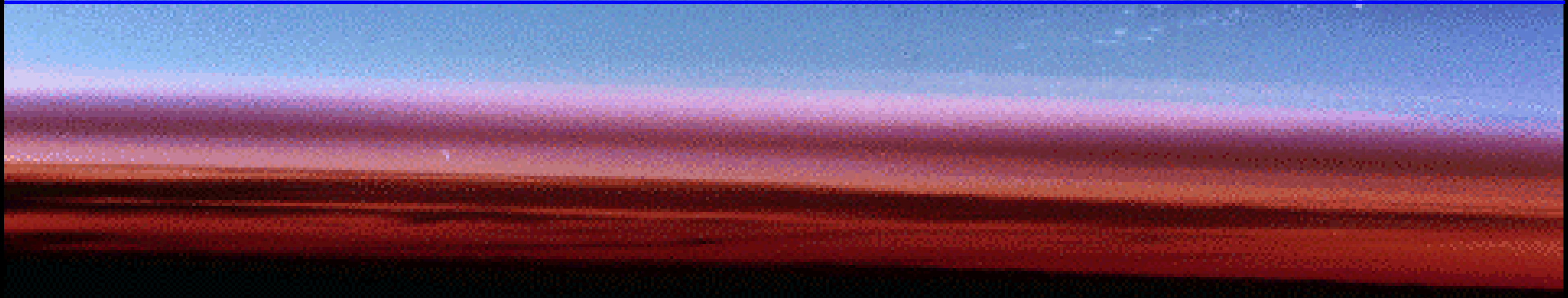
→ We have a very good understanding of Upper stratospheric chemistry: The Protocol is working on Chlorine

The ability to determine trend changes early with high confidence depends on:

1. Data quality (ozone and proxies)
2. Density of data coverage (time and space)
3. Quality of the model fitting

Conclusions

1. Ozone measurements by satellites and international ground stations show compelling evidence of the BEGINNING of the recovery of the ozone in the UPPER stratosphere AND in the TOTAL STRATOSPHERIC COLUMN.



Conclusions

1. Ozone measurements by satellites and international ground stations show compelling evidence of the BEGINNING of the recovery of the ozone in the UPPER stratosphere AND in the TOTAL STRATOSPHERIC COLUMN.

2. The ozone amount is near a minimum.

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Conclusions

1. Ozone measurements by satellites and international ground stations show compelling evidence of the BEGINNING of the recovery of the ozone in the UPPER stratosphere AND in the TOTAL STRATOSPHERIC COLUMN.

2. The ozone layer is near it’s minimum.

3. The chlorine amounts (from CFC releases at the surface) are decreasing at Earth’s surface and are peaking in the upper stratosphere as a result of the Montreal Protocol and its amendments.

Conclusions

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6. We now have compelling evidence for the most significant environmental success story of the 20th century: The entire stratospheric ozone column is experiencing the first stage of recovery.

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Future ?

1. What is the attribution of the ozone recovery in the lower stratosphere?

2. How will global climate changes affect the ozone recovery?

3. What observational capacity is necessary to adequately answer #1 and #2?
    1. Measure ozone evolution
    2. Measure climate changes

http://nsstc.uah.edu/atmchem/

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